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Ganapathi et al.

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(54) **AUTHENTICATION SYSTEM HAVING A FLEXIBLE IMAGING PRESSURE SENSOR**

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Related U.S. Application Data

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(51) **Int. Cl.**
G01D 7/00 (2006.01)

(52) **U.S. Cl.** **73/862.046**; 73/862.041; 73/862.042; 73/862.043; 73/862.044; 73/862.045

(58) **Field of Classification Search** 73/862.041–862.046
See application file for complete search history.

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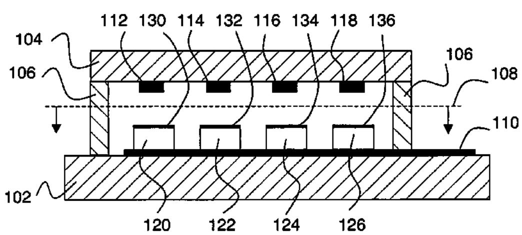
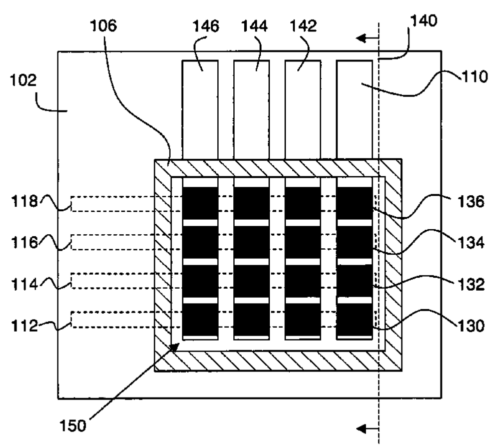
(57) **ABSTRACT**

A sensor for a textured surface (e.g., a fingerprint) is provided. The sensor includes a flexible substrate and a flexible membrane supported above the substrate by one or more spacers. The sensor also includes multiple pressure sensor elements responsive to a separation between parts of the membrane and corresponding parts of the substrate. The membrane is conformable to the textured surface being sensed, so the variation in separation between substrate and membrane is representative of the textured surface being sensed. Such pressure sensors can be included in fingerprint authentication subsystems including associated integrated electronic circuitry (e.g., encryption, image processing, fingerprint matching, communication and/or location determination circuitry). Such subsystems can be included in various access control systems (e.g., smart cards and mobile electronics). Unpackaged IC chips can be included on the flexible substrate or can be disposed on a separate electronics substrate attached to the sensor.

25 Claims, 10 Drawing Sheets





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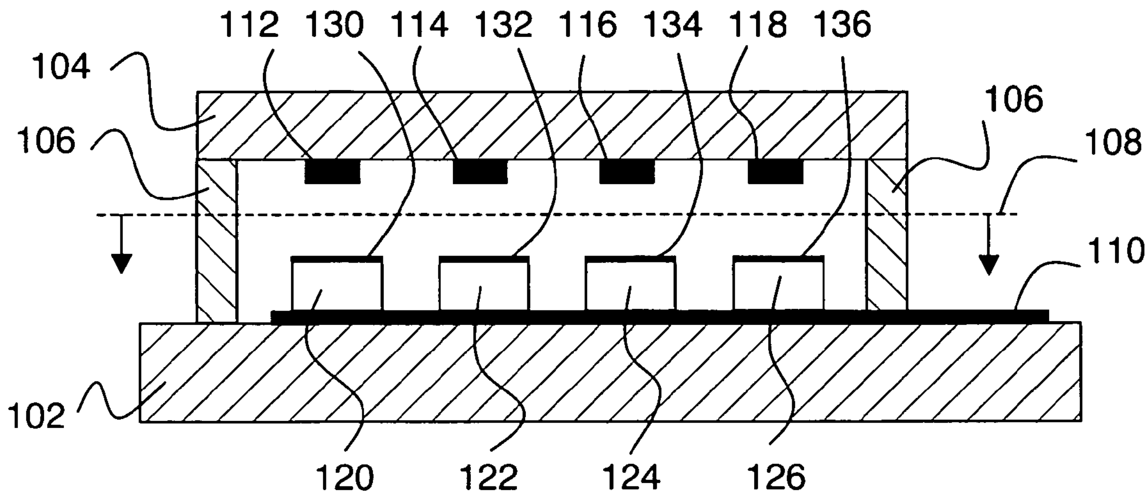
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Fig. 1a

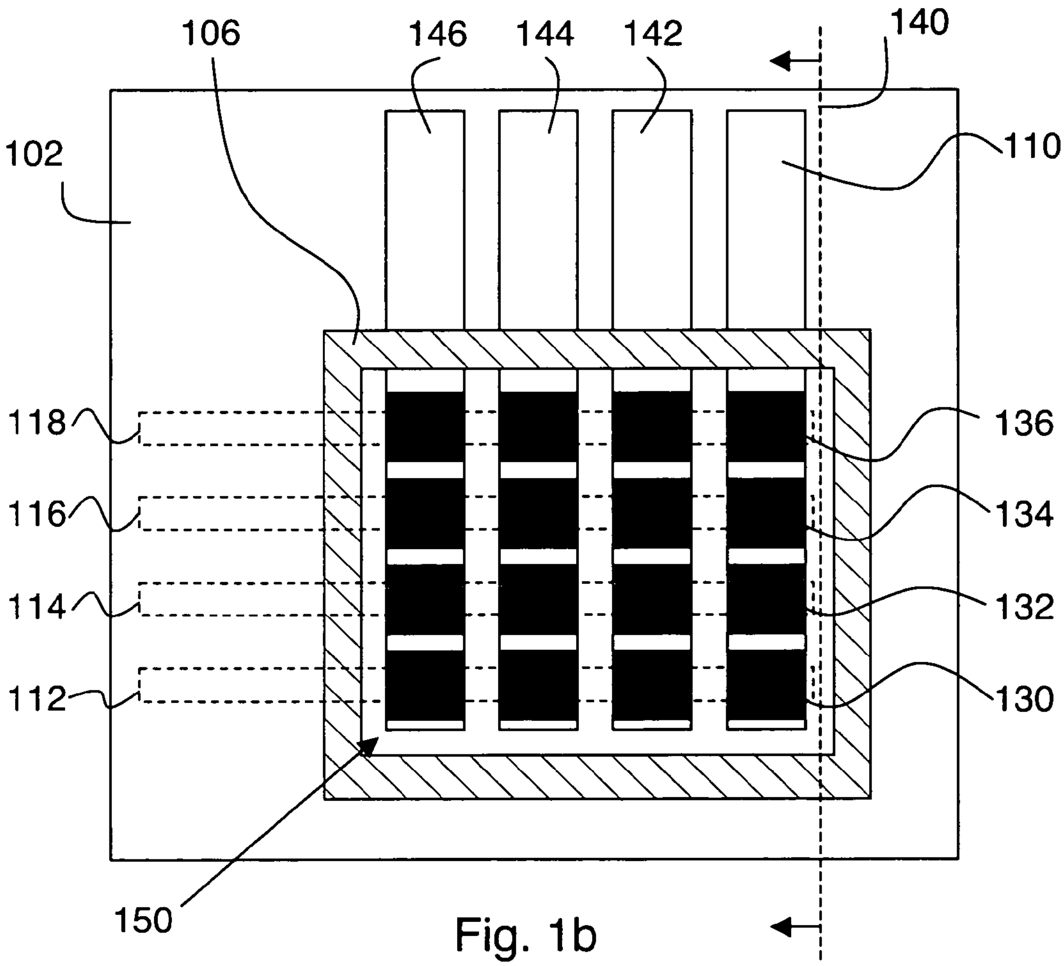
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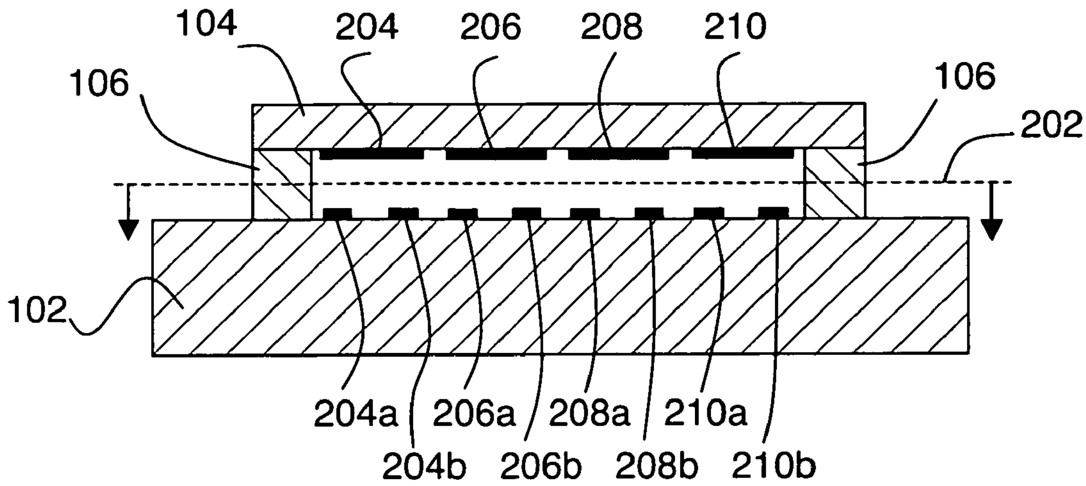
Fig. 1b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210b

Fig. 2a

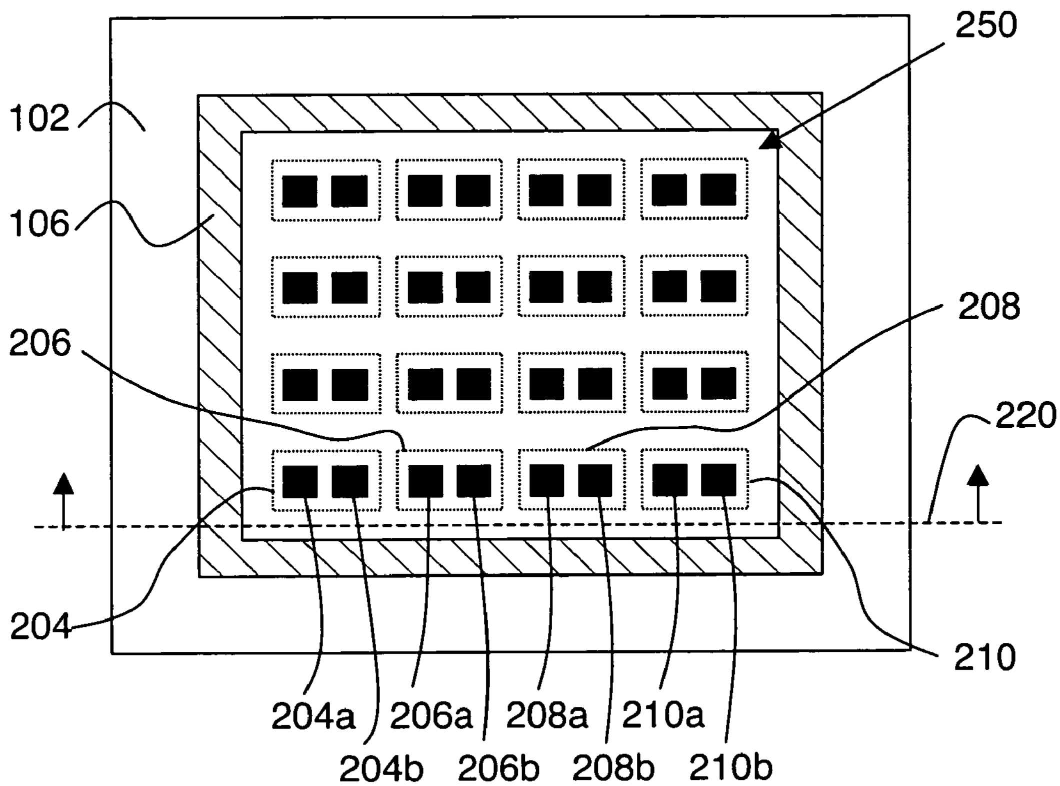
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Fig. 2b

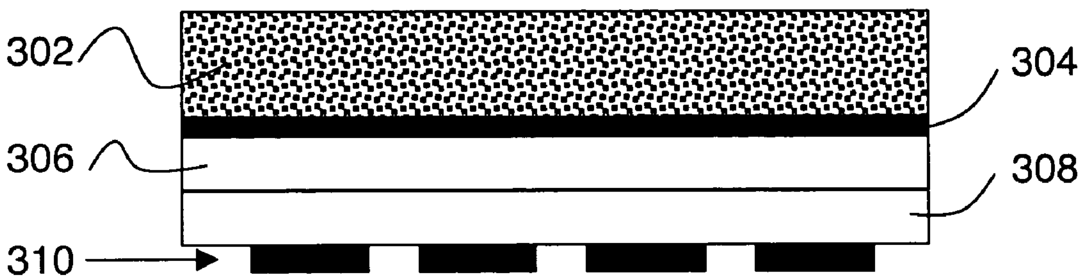


Fig. 3

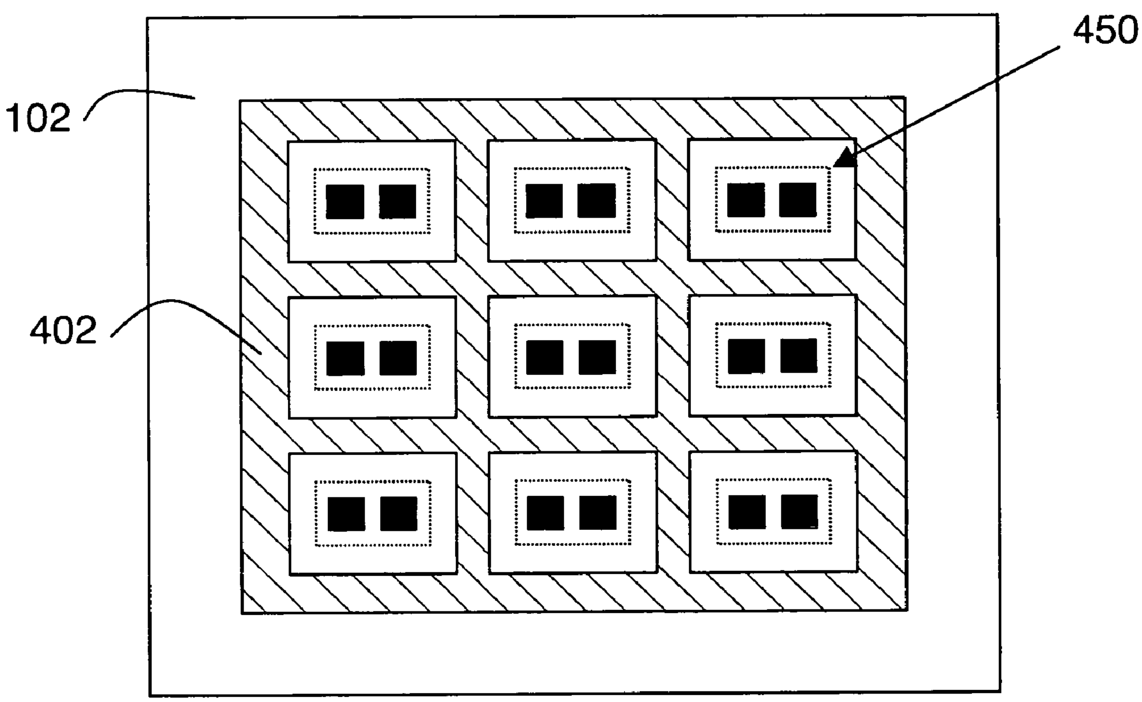


Fig. 4

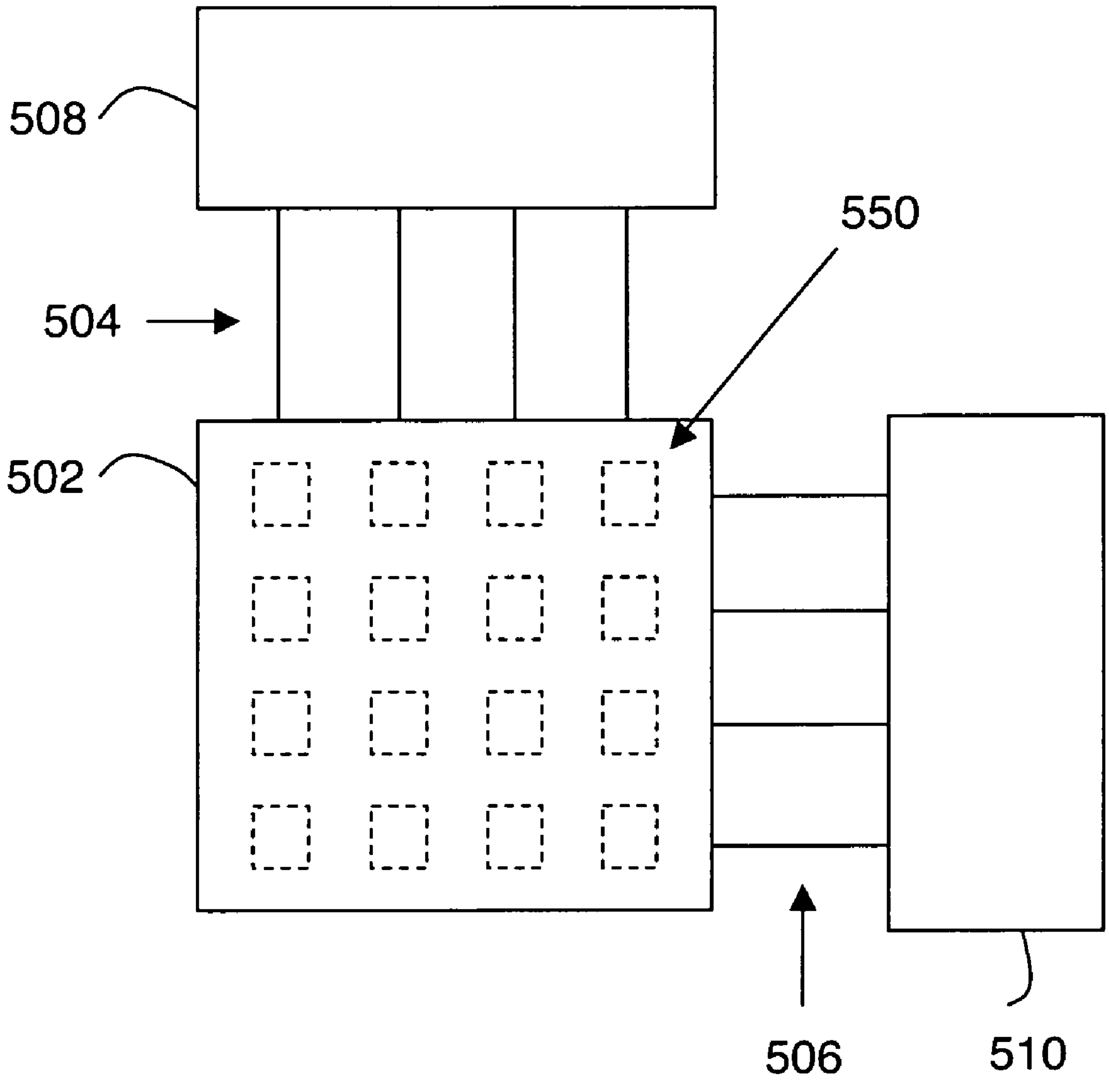


Fig. 5

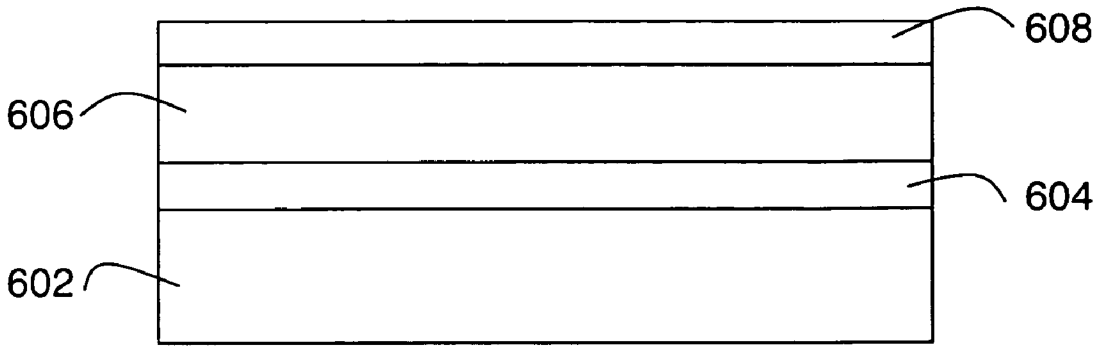


Fig. 6a

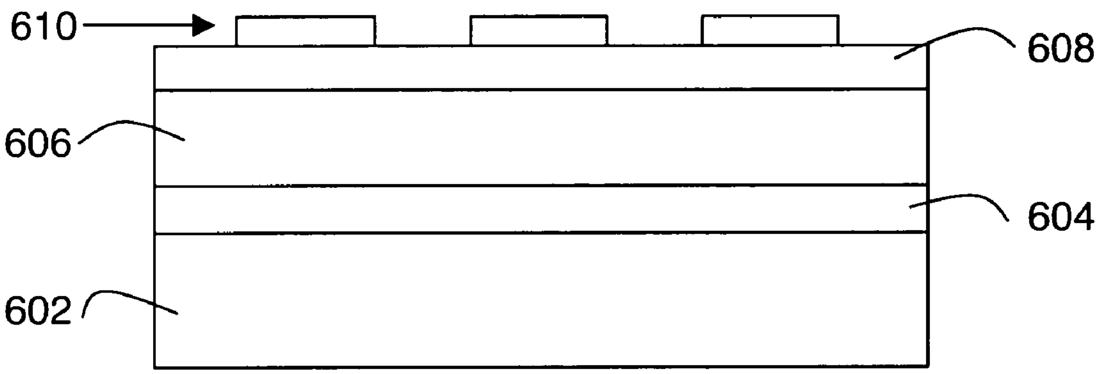


Fig. 6b

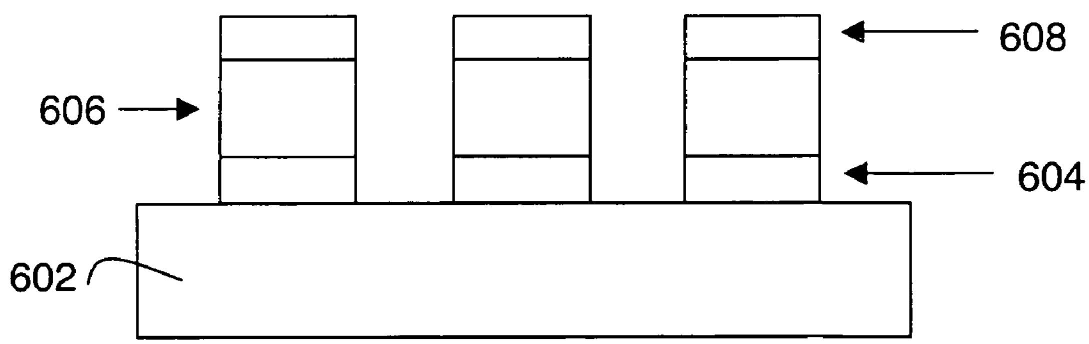


Fig. 6c

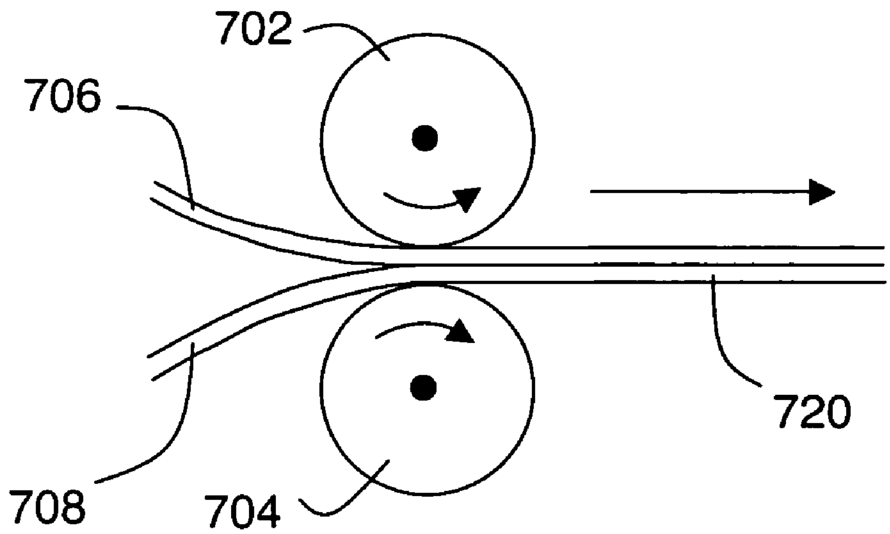
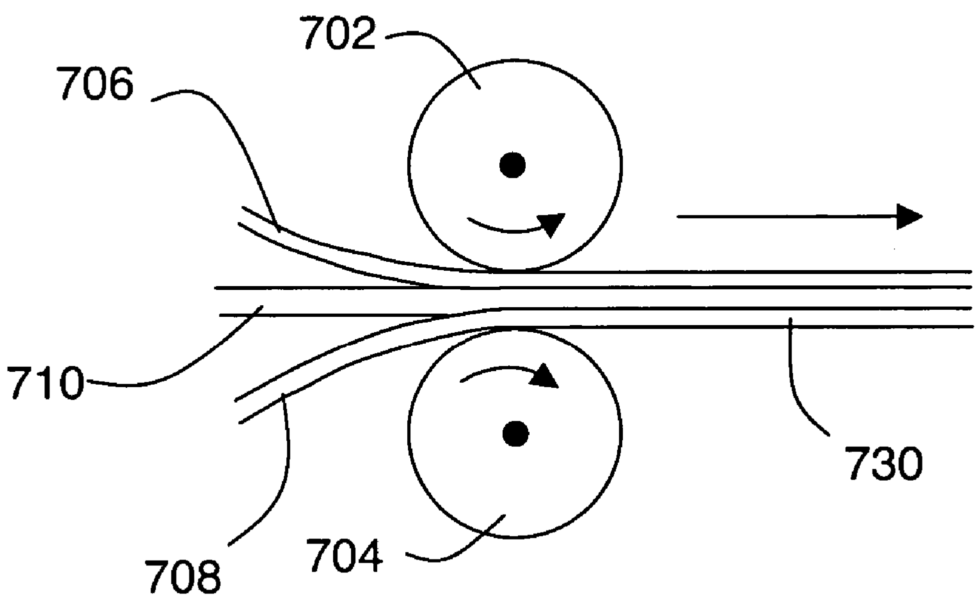


Fig. 7a



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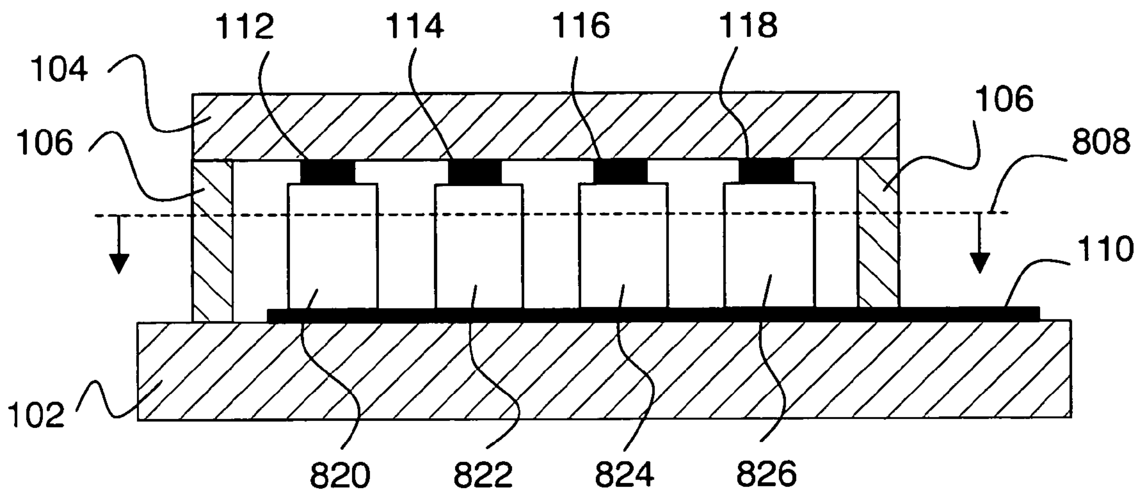
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Fig. 8a

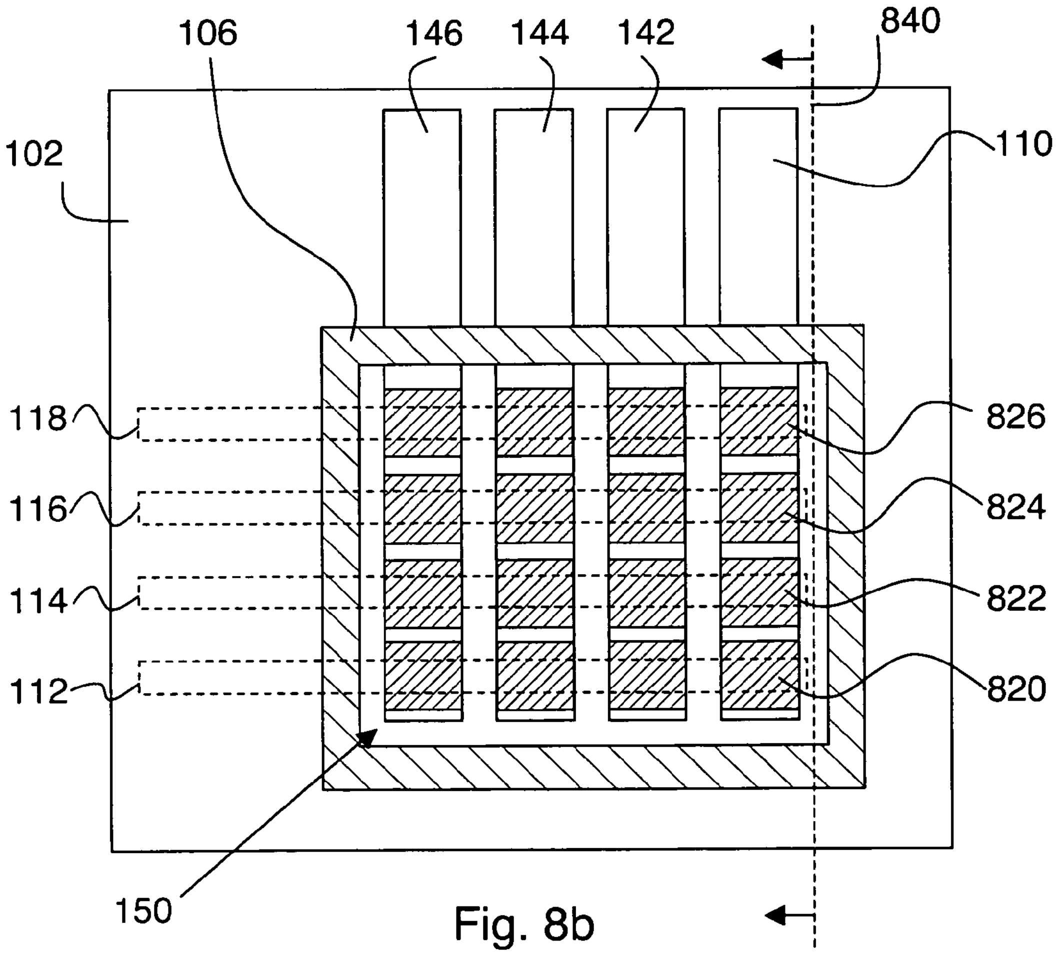
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Fig. 8b

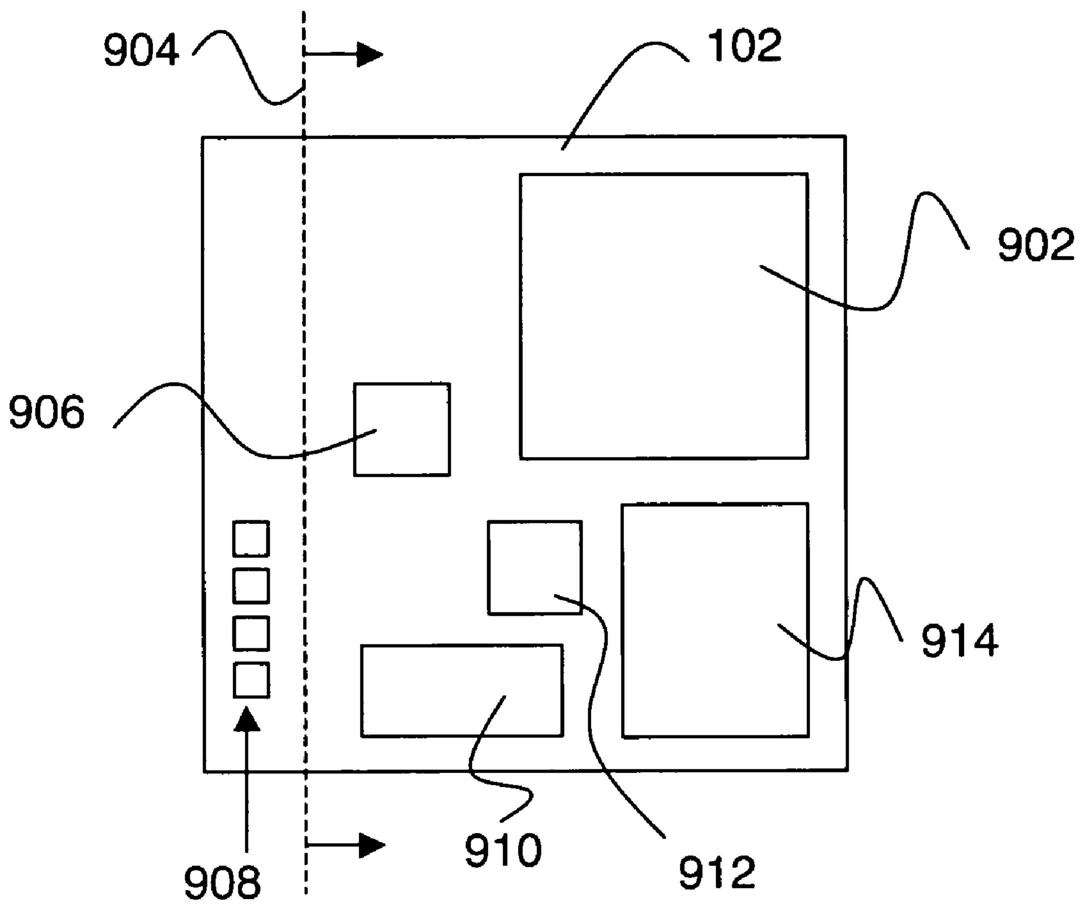

Fig. 9a

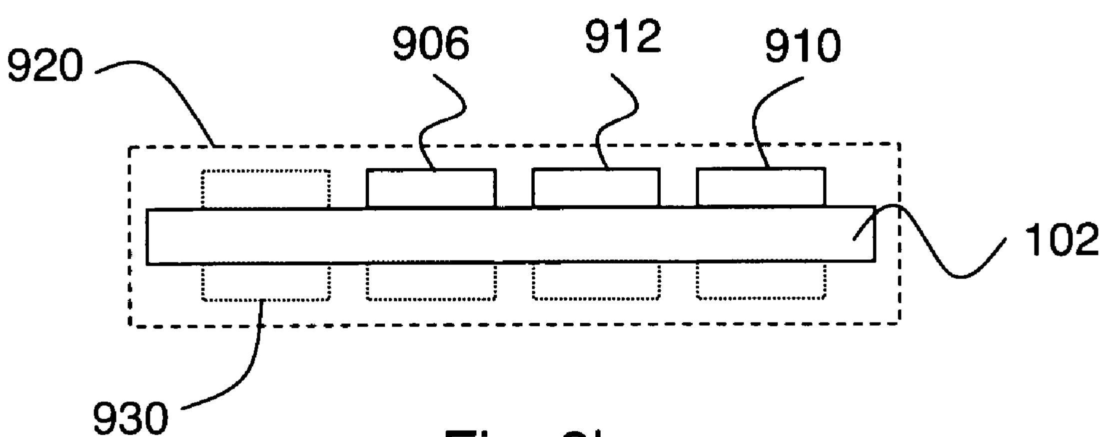

Fig. 9b

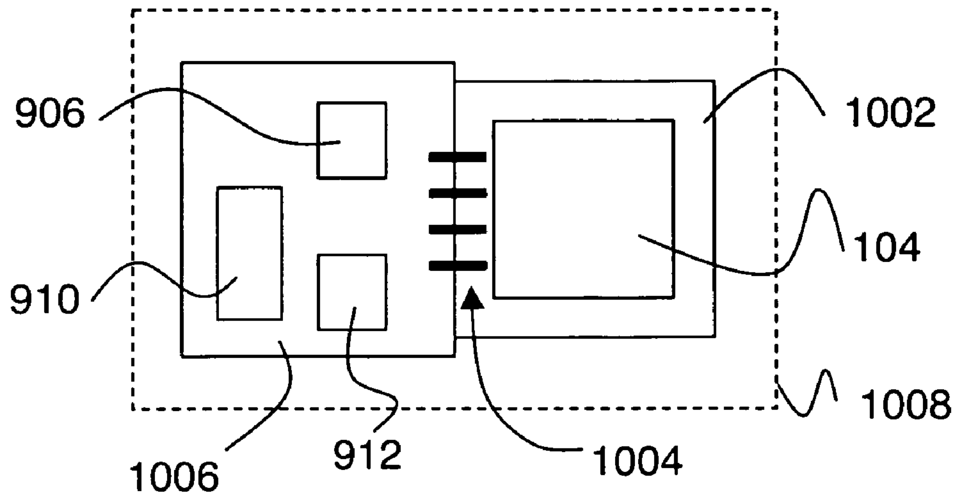

Fig. 10a

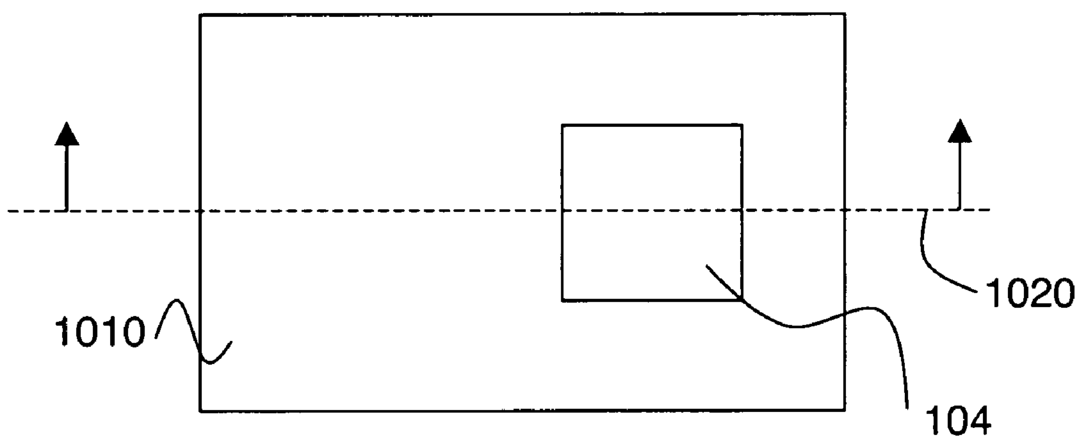

Fig. 10b

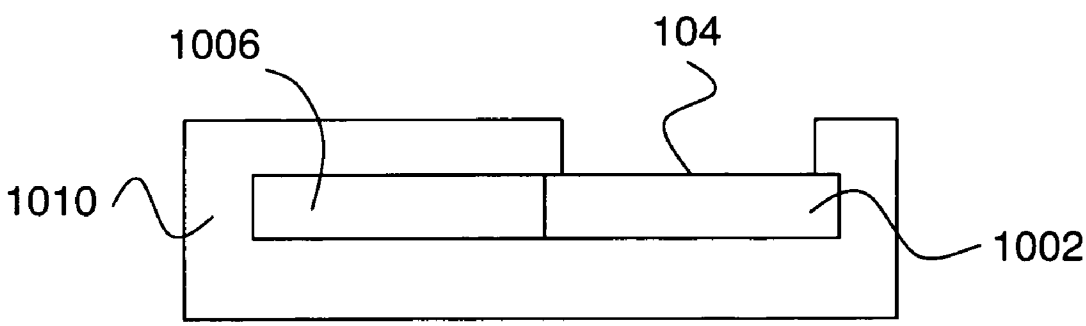

Fig. 10c

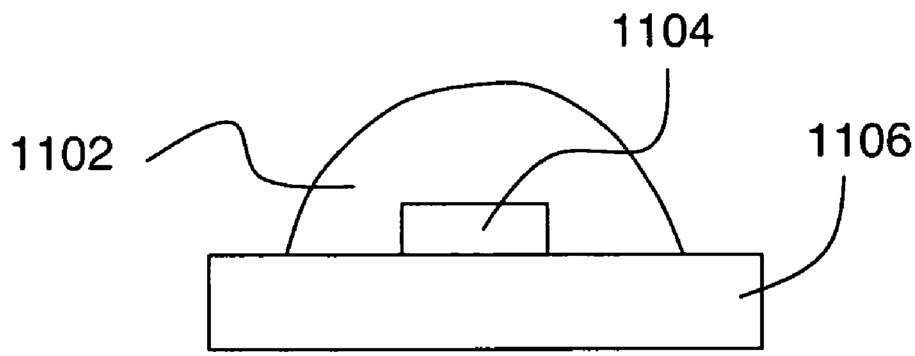

Fig. 11a

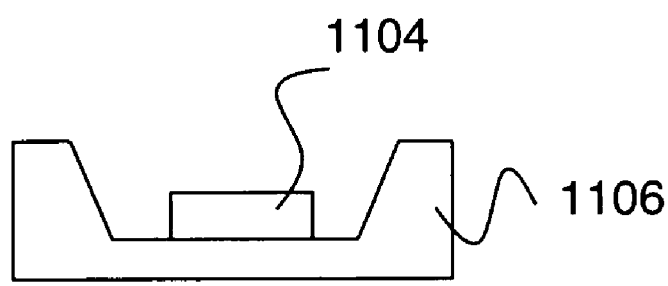

Fig. 11b

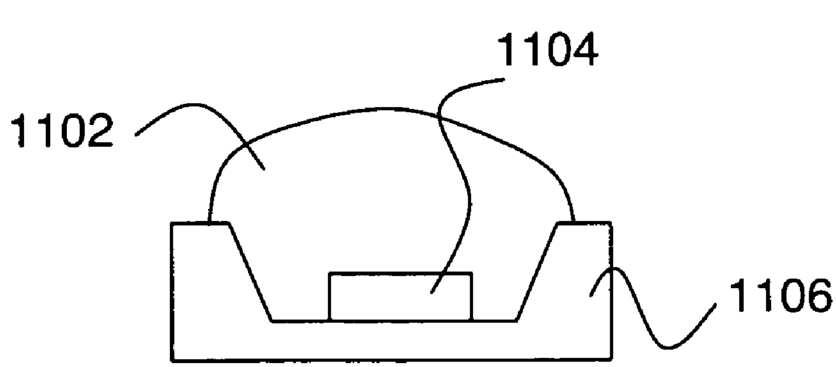

Fig. 11c

AUTHENTICATION SYSTEM HAVING A FLEXIBLE IMAGING PRESSURE SENSOR

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation in part of U.S. patent application Ser. No. 11/145,534, filed on Jun. 2, 2005, and entitled “Flexible Imaging Pressure Sensor”.

FIELD OF THE INVENTION

This invention relates to pressure sensors for providing a tactile image of a textured surface, such as a fingerprint.

BACKGROUND

Security and identification often relies on fingerprint data. Accordingly, sensors for providing fingerprint images have been under development for some time. Many such sensors employ an array of sensor pixels making direct contact with a finger. Readout of the sensor pixels provides fingerprint image data. Known approaches for providing such sensor pixels include capacitive sensing (e.g., as in U.S. Pat. No. 6,694,269), and temperature or pressure sensing (e.g., as in U.S. Pat. No. 4,429,413). Further references relating to pressure sensing include: U.S. Pat. No. 5,844,287, U.S. Pat. No. 6,672,174, U.S. Pat. No. 6,578,436, and U.S. Pat. No. 2002/0121145.

In many cases, sensors based on pressure sensing include a flexible membrane that conforms to the valleys and ridges of an applied fingerprint. The membrane is typically suspended above a rigid substrate that provides mechanical support. Each sensor pixel is responsive to a separation between the membrane and substrate. The substrate often includes integrated electronic circuitry (e.g., pixel addressing circuitry). Known examples of this general approach include: U.S. Pat. No. 4,577,345, U.S. Pat. No. 5,745,046, U.S. Pat. No. 5,400,662, and U.S. Pat. No. 5,079,949. In practice, implementation of such sensor approaches is often excessively costly. A typical integrated fingerprint sensor chip dimension is 15 mm×15 mm to accommodate the size of a normal fingerprint and the area of the integrated processing circuitry. Such large chips are costly to fabricate, since the number of chips per semiconductor wafer is relatively low. Furthermore, sensors having rigid and breakable substrates (e.g., conventional silicon substrates) cannot be used for applications such as smart credit/identity cards where the sensor must survive a certain degree of flexure.

Another sensor approach is considered in an article by Young et al., entitled “Novel Fingerprint Scanning Arrays Using Polysilicon TFTs on Glass and Polymer Substrates”, and published in IEEE Electron Device Letters 18 (1), pp 19-20, January 1997. In this work, the substrate is flexible, alleviating the above-mentioned breakage problem, and capacitive sensing is employed. Since capacitive sensing entails no significant relative motion of sensor parts in operation, mechanical complications resulting from substrate flexure are presumably avoided. However, the capacitive sensing in this work relies on integrated thin film transistors to amplify signals. Although thin film transistors deposited on flexible substrates are known (e.g., as in U.S. Pat. No. 6,680,485), it would be preferable to avoid the use of active devices integrated with the sensor array in order to reduce cost. In addition, the polymeric transistors used in such works can be unreliable in commonly encountered environmental conditions such as high humidity (which causes polymer transistor degradation). Furthermore, the fabrication of more traditional transistors, such as thin film transistors, requires exposure of the substrate to high temperatures during processing, which can cause degradation of typical polymer based flexible substrates.

Another flexible sensor is considered in an article by Engel et al., entitled “Development of polyimide flexible tactile sensor skin”, and published in the Journal of Micromechanics and Microengineering, 13, pp 359-366, 2003. In this work, each pixel includes a relatively thin membrane that flexes (or doesn’t flex) responsive to the presence (or absence) of a fingerprint ridge. Flexure of the membrane is sensed by a strain gauge integrated with the membrane. Since the strain gauge is in the membrane, the substrate is not a functional part of each pixel. Instead, the substrate provides overall mechanical support, and may include circuitry for reading out the sensor array. A disadvantage of this approach is that the strain gauge output is analog. It is often preferred for fingerprint sensors to provide inherently digital outputs, since a digital image is often required in practice and post-conversion of an analog sensor image to a binary image is frequently error-prone.

Accordingly, it would be an advance in the art to provide a flexible fingerprint sensor overcoming the above-identified shortcomings. More specifically, a flexible fingerprint sensor providing an inherently binary output would be an advance in the art. A further advance in the art would be a flexible fingerprint sensor providing an inherently binary output and having only passive components in the sensor array.

SUMMARY

The present invention provides a sensor for a textured surface (e.g., a fingerprint). The sensor includes a flexible substrate and a flexible membrane supported above the substrate by one or more spacers. The sensor also includes multiple pressure sensor elements responsive to a separation between parts of the membrane and corresponding parts of the substrate. The membrane is conformable to the textured surface being sensed, so the variation in separation between substrate and membrane is representative of the textured surface being sensed. A preferred sensor array arrangement has a set of parallel substrate electrodes on the substrate facing the membrane and a set of parallel membrane electrodes on the membrane facing the substrate, where the substrate and membrane electrodes are perpendicular to each other. The sensor array is preferably an entirely passive structure including no active electrical devices, to reduce cost. Row and column addressing circuitry can be provided as separate units (e.g., ASIC chips) to be hybrid integrated with the sensor array.

The present invention provides several significant advantages. The flexibility of the substrate permits sensors according to the invention to be used in applications where rigid sensors would break, such as credit card and identity card applications. The flexible substrate also permits high-volume fabrication methods (e.g., roll-level processing), to reduce cost. In preferred embodiments where the substrate and membrane define a switch array, the sensor output is advantageously an inherently binary signal corresponding to whether or not the relevant switch is open or closed. Here a switch is regarded as any structure having an electrical resistance responsive to a mechanical input (e.g., having movable electrical contacts, including a pressure sensitive resistor, etc.).

Such pressure sensors can be included in fingerprint authentication subsystems including associated integrated electronic circuitry (e.g., encryption, image processing, fingerprint matching, communication and/or location determi-

nation circuitry). Such subsystems can be included in various access control systems (e.g., smart cards and mobile electronics). Unpackaged IC chips can be included on the flexible substrate or can be disposed on a separate electronics substrate attached to the sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1***a-b* show cutaway side and top views, respectively, of an embodiment of the invention.

FIGS. **2***a-b* show cutaway side and top views, respectively, of another embodiment of the invention.

FIG. **3** shows a detailed view of a preferred top membrane suitable for use with the invention.

FIG. **4** shows an alternative spacer arrangement for use with the invention.

FIG. **5** shows remotely located row and column addressing circuitry for use with the invention.

FIGS. **6***a-c* show a preferred sequence of processing steps for fabricating part of an embodiment of the invention.

FIGS. **7***a-b* show bonding methods suitable for fabricating some embodiments of the invention.

FIGS. **8***a-b* show cutaway side and top views, respectively, of an embodiment of the invention.

FIGS. **9***a-b* show top and side views, respectively, of an integrated fingerprint authentication subsystem according to an embodiment of the invention.

FIGS. **10***a-c* show several views of an integrated fingerprint authentication subsystem according to an alternate embodiment of the invention.

FIGS. **11***a-c* show various stress relief approaches suitable for use in integrated fingerprint authentication subsystems according to the invention.

DETAILED DESCRIPTION

FIGS. **1***a-b* show cutaway side and top views, respectively, of an embodiment of the invention. More specifically, FIG. **1***a* shows a cutaway view along line **140** on FIG. **1***b*, and FIG. **1***b* shows a cutaway view along line **108** on FIG. **1***a*. A flexible substrate **102** and a flexible membrane **104** are connected to a spacer **106**. Membrane **104** is conformable to a textured surface to be sensed (e.g., a fingerprint). A plurality of pressure sensor elements **150** is included, each pressure sensor element being responsive to a separation between part of the membrane and a corresponding part of the substrate. Spacer **106** determines, in part, a nominal separation between membrane **104** and substrate **102** for each pressure sensor element. Here the nominal separation is the separation between membrane and substrate when no textured surface is making contact with the top surface of membrane **104**. As used herein, "flexible" is taken to refer to materials or structures having a Young's modulus of less than 25 GPa. For structures including multiple material compositions (e.g., a multi-layer laminate), the smallest Young's modulus of the materials in the structure is regarded as the Young's modulus of the structure.

Suitable materials for substrate **102** include, but are not limited to: polyimides, aromatic fluorine polyesters, polyethersulfone, polysulfones, polyacrylates, polycarbonates, polyetheretherketone, polyethylene naphthalate (PEN), blocked isocyanates, silicone based elastomers, polyamides, polyether imides, polymethacrylates, polyolefins, poly(ethylene-acrylate) copolymers, poly(ethylene-methacrylate) copolymers, polyethylene terephthalate (PET), polynaphthalene terephthalate, polydienes, poly(styrene-diene) block copolymers, poly(vinyl halides), polyurethanes, poly(urethane acrylates), poly(urethane methacrylates), poly(dimethyl siloxanes), and ionomers. The substrate material preferably remains flat during and after various processing steps, such as metallization and etching. Thermal stability, low moisture uptake and chemical resistance of the substrate are also preferred. In some fingerprinting applications, polyimides (e.g., Kapton®), PEN and PET are preferred substrate materials.

Suitable materials for membrane **104** include, but are not limited to: polyimides, aromatic fluorine polyesters, polyethersulfone, polysulfones, polyacrylates, polycarbonates, polyetheretherketone, polyethylene naphthalate (PEN), blocked isocyanates, silicone based elastomers, polyamides, polyether imides, polymethacrylates, polyolefins, poly(ethylene-acrylate) copolymers, poly(ethylene-methacrylate) copolymers, polyethylene terephthalate (PET), polynaphthalene terephthalate, polydienes, poly(styrene-diene) block copolymers, poly(vinyl halides), polyurethanes, poly(urethane acrylates), poly(urethane methacrylates), poly(dimethyl siloxanes), and ionomers. In some fingerprinting applications, polyimides (e.g., Kapton®), PEN and PET are preferred membrane materials.

Suitable materials for spacer **106** include, but are not limited to: silicones, polyurethanes, polyamides, polyimides, polyacrylates, polymethacrylates, poly(glycidyl ethers), poly (ethylene-acrylate) copolymers, poly(ethylene-methacrylate) copolymers, polydienes, poly(styrene-diene) block copolymers, poly(vinyl halides), polyurethanes, poly(urethane acrylates), poly(urethane methacrylates), and poly (dimethyl siloxanes). The spacer is preferably a pressure sensitive or other curable adhesive. The nominal separation between membrane and substrate is preferably as small as possible given other design constraints, in order to reduce flexure distortion and internal pressure variation.

Various arrangements are possible for pressure sensor elements **150**. FIGS. **1***a-b* show a preferred arrangement where a plurality of substantially parallel membrane electrodes **112**, **114**, **116**, and **118** are disposed on the membrane, and a plurality of substantially parallel substrate electrodes **110**, **142**, **144**, and **146** are disposed on the substrate. Preferably the membrane and substrate electrodes are substantially perpendicular to each other, as shown, although they can intersect at any angle. Since the pressure sensor elements are defined by intersections of the membrane and substrate electrodes, row and column addressing of the electrodes can be employed to interrogate each sensor element. Each pressure sensor element can be regarded as including a part of its membrane electrode as a first contact and part of its substrate electrode as a second contact. Gold is a suitable material for the membrane and substrate electrodes, and typical electrode dimensions for fingerprint applications are 15 μm wide, 35 μm spacing and 100 nm thickness. The invention can be practiced with other electrode compositions and dimensions. The invention can be practiced with any number of rows and columns in the pressure sensor element array. An array of 256 rows and 256 columns has been found suitable for fingerprint applications.

The embodiment of FIGS. **1***a-b* includes several preferred electrical design features. Although embodiments of the invention can have active electrical devices (e.g., transistors) integrated with the sensor array, it is preferable for the sensor array to be entirely passive (i.e., including only resistors, capacitors, inductors or any combination thereof). Thus the pressure sensor elements preferably provide a resistance, a capacitance or an inductance responsive to the separation between substrate and membrane at the location of the sensor element. In this example, resistors such as **120**, **122**, **124**, and **126** are disposed on the substrate electrodes and can make contact with corresponding membrane electrodes when the membrane deforms responsive to an applied fingerprint. Thus the resistance between a row and a column electrode is either very high (corresponding to an open circuit) or relatively low (when contact is made). This arrangement can be regarded as an array of normally-open switches. Preferably, the resistor value is between about 25 kΩ and about 5 MΩ, and is more preferably about 1 MΩ. Suitable materials for these resistors include, but are not limited to: co-sputtered metals and ceramics, tantalum oxide, polysilicon, amorphous silicon, conductive polymer composites, polymer thick film resistors, carbon nanotube composites, composite plastics, composite elastomers, and intrinsically conductive polymers.

It is preferred for the resistors to be wider than the membrane electrodes, as shown on FIGS. **1***a-b*. This arrangement provides increased tolerance for misalignment of the membrane electrodes relative to the resistors, and thus for the membrane relative to the substrate.

In the case where the sensing element includes an active device, various forms of transistor or diode can be used, such as a p-i-n diode, a thin film transistor, or a polymer transistor. Finally, various combinations of active and passive devices can be employed, such as the case where a resistor is placed in series with a diode or a transistor.

It is also preferred for the pressure sensor elements to have electrical impedances that change by a large percentage between the open and the closed condition, so that simple electronic comparators can be used to provide binary output signals as opposed to analog output signals. In the example of FIGS. **1***a-b*, the pressure sensor output is binary, since the electrical current measured during addressing of a particular cell exceeds or falls below a certain threshold value, depending on whether or not contact is made between the resistor and the mating electrode. An example of an embodiment providing analog output signals is an arrangement similar to that of FIGS. **1***a-b* except that capacitance between substrate and membrane is sensed. Such capacitive sensing provides an analog signal, since the capacitance varies continuously as the separation between membrane and substrate varies. For such capacitive sensing, active circuitry integrated with the sensor array, e.g. as described above, in the form of diodes or transistors, is suitable for processing the analog signals.

Although not required, it is also preferred to include contact layers such as **130**, **132**, **134** and **136** disposed on a surface of resistors **120**, **122**, **124**, and **126** respectively facing membrane **104**. The contact layers are preferably gold layers about 100 nm thick, although other compositions (e.g., conductive polymers) and thicknesses can also be employed. With this arrangement, the contact that can be made between substrate and membrane in each sensor element is a gold to gold contact, as opposed to a gold to resistor contact, which improves device reliability. In this example, the resistors are disposed on the substrate electrodes. Alternatively, the resistors can be disposed on the membrane electrodes. In this alternative case, the contact layers are disposed on surfaces of the resistors facing the substrate electrodes. In some embodiments, a contact layer is also provided on top of an electrode surface facing the resistors. For example, the membrane electrodes in FIGS. **1***a-b* can be covered by corresponding contact layers. Such contact layers can be useful for protecting soft contact materials (e.g., gold) from mechanical wear.

Another preferred electrical design feature of the example of FIGS. **1***a-b* is the resistor configuration. More specifically, FIGS. **1***a-b* show vertical resistors through which current flows vertically, normal to the plane of the sensor array, on FIGS. **1***a-b*. An alternative includes horizontal resistors, in which current flows along the plane of the sensor array, fabricated on the substrate and/or membrane. Each such resistor is connected to a contact at one end and to an electrode at the other end. The contacts allow the opening and closing of the individual switch at the intersection of each row and column electrode pair. In this approach, the vertical resistance of the closed contact is negligible compared to the resistance provided by the horizontal resistor. The vertical resistor configuration of FIGS. **1***a-b* is preferred because it is easier to fabricate than the horizontal resistor approach.

The embodiment of FIGS. **1***a-b* also includes several preferred mechanical design features. A first key consideration is balancing the mechanical properties of the membrane and substrate. More specifically, the substrate needs to be flexible enough so that it will not break when affixed to a flexible surface (e.g., a credit card, identity card, etc). The substrate also needs to be stiffer than the membrane to provide mechanical support to the membrane via the spacer. A key parameter is flexural rigidity (D), given by

$$D = \frac{Et^3}{12(1-\nu^2)}, \tag{1}$$

where E is the elastic modulus, ν is Poisson's ratio, and t is the film thickness. Since most engineering polymers have 2 GPa≦E≦6 GPa and 0.33≦ν≦0.4, the thickness t is the main parameter of interest. The importance of thickness as a design parameter is also enhanced by the cubic dependence of rigidity on thickness.

Another consideration relating to mechanical design is maintaining proper registration between membrane and substrate features as the sensor is flexed or bent during operation. The tensile strain ε in bending is approximately given by

$$\varepsilon \propto \left(\frac{F}{\mathrm{Eat}}\right)^{2/3}, \tag{2}$$

where F is the applied normal force to a square sensor having sides of length a. For a sensor having a=12.8 mm and 35 μm by 15 μm sensor contacts, the strain ε should not exceed 0.2%.

In view of these considerations, the substrate rigidity D_S is preferably greater than the membrane rigidity D_M (i.e., $D^M<D_S<10^6\ D_M$, more preferably $50\ D_M<D_S<500\ D_M$). The substrate rigidity D_S is preferably in a range from about 10^{-7} N-m to about 10^{-4} N-m, and is more preferably in a range from about 10^{-6} N-m to about 10^{-5} N-m. The membrane rigidity D_M is preferably in a range from about 10^{-11} Nm to about 10^{-6} N-m and is more preferably in a range from about 10^{-8} N-m to about 10^{-6} N-m. The gap between membrane and substrate is preferably in a range from about 10 μm to about 150 μm.

In many cases of interest, the substrate and membrane have similar elastic properties. In these cases, preferred mechanical configurations can also be specified in terms of relations between substrate thickness t_S and membrane thickness t_M. Preferably, $t_M \leqq t_S \leqq 1000\ t_M$ and more preferably $t_M \leqq t_S \leqq 10\ t_M$. Such thickness relations are also applicable in cases where the substrate and/or membrane are laminates including multiple layers, if the substrate and membrane have comparable flexural rigidities.

FIGS. **2***a-b* show cutaway side and top views, respectively, of another embodiment of the invention. More specifically, FIG. **2***a* shows a cutaway view along line **220** on FIG. **2***b*, and

FIG. **2***b* shows a cutaway view along line **202** on FIG. **2***a*. The embodiment of FIGS. **2***a-b* differs from the embodiment of FIGS. **1***a-b* in the arrangement of the pressure sensor elements. More specifically, pressure sensor elements **250** on FIGS. **2***a-b* each include a pair of contact electrodes disposed on the substrate, such as **204***a, b*, **206***a,b*, **208***a,b* and **210***a, b* and a corresponding electrically conductive region such as **204**, **206**, **208**, and **210** respectively, disposed on the membrane. Operation of the embodiment of FIGS. **2***a-b* is similar to the operation of the embodiment of FIGS. **1***a-b*. Localized contact between membrane and substrate closes electrical switches (e.g., electrodes **204***a* and **204***b* can be connected by contact from region **204**), and the pattern of open and closed switches across the array is representative of the textured surface being sensed. An advantage of the embodiment shown in FIGS. **2***a-b* is that, for appropriate configuration of electrodes, it does not require a very precise alignment between the membrane and the substrate when the two are bonded together with the spacer in between them. The pressure sensor element arrangements shown in FIGS. **1***a-b* and **2***a-b* are two exemplary sensor element arrangements. Any arrangement of any type of pressure sensor element can also be employed in practicing the invention.

In the preceding examples, membrane **104** preferably satisfies multiple constraints. More specifically, a compliant membrane is desirable to provide high-fidelity imaging of a fingerprint image. A rigid membrane is desirable to provide scratch resistance. A highly elastic membrane with high elongation before deformation characteristics is desirable in order to prevent embossing (i.e., plastic deformation), either in operation or as a result of scratch testing. Finally, it is desirable for the membrane to provide ESD protection for other sensor components, which requires electrical conductivity of the membrane. More specifically, the side of the membrane which a user will touch in operation should be electrically conductive. In view of these multiple constraints, membrane **104** is preferably a laminate including multiple layers having different compositions. An example of a preferred membrane laminate follows.

FIG. **3** shows a detailed view of a preferred top membrane suitable for use with the invention. A top layer **302** is an elastic film having nanoparticle inclusions. The nanoparticles are mechanically hard, and electrically conductive. Top layer **302** preferably has a relatively low coefficient of friction. A thin metallization layer **304** has high electrical conductivity and is electrically grounded to protect other sensor components from ESD. Layer **306** is a relatively stiff polymer layer that provides dimensional stability to the laminate, which is important to maintain feature registration between membrane and substrate. Layer **308** is an elastomer layer resistant to embossing. Membrane electrodes **310** are disposed on layer **308**.

The arrangement of FIG. **3** satisfies the above-identified constraints as follows. ESD protection is provided by the combination of grounded and highly conductive layer **304** and conductive layer **302**. Embossing is most likely to occur as a result of concentrated forces at the electrodes, so elastomer layer **308** is disposed adjacent to the membrane electrodes. Scratch resistance combined with conformability to a fingerprint pattern is provided by a relatively soft top layer **302** having mechanically hard nanoparticle inclusions. Layer **306** provides mechanical support for the membrane as a whole. Adjustment of the thickness and mechanical properties of layer **306** is a preferred method for designing the flexural rigidity D_M of the laminated membrane in accordance with the above-identified principles.

In some embodiments of the invention, substrate **102** is a multi-layer laminate and/or has particulate inclusions. Such substrates are likely to be suitable in cases where a set of requirements placed on the substrate are difficult to meet with a homogeneous, single-layer structure.

A preferred arrangement for spacer **106** defines a global cavity including all of the pressure sensor elements, as shown on FIGS. **1***a* and **2***b*. Proper mechanical design of flexible substrate **102** combined with flexible membrane **104**, as indicated above, enables this global cavity spacer arrangement. Such global cavity arrangements have been found suitable for arrays having a large number of sensors (e.g., 256×256 or even more). FIG. **4** shows an alternative spacer arrangement for use with the invention. Spacer **402** defines a local cavity corresponding to each of pressure sensor elements **450**. The invention is not limited to these two exemplary spacer arrangements, and can be practiced with any spacer arrangement that provides a nominal separation between membrane and substrate in the pressure sensor elements. For example, the spacer can define several cavities each including one or more pressure sensor elements. The spacer can also include localized standoffs, each corresponding to one or more pressure sensor elements, for providing a nominal separation between membrane and substrate. An art worker can select a suitable spacer configuration based on the following considerations.

A preferred embodiment of a spacer having local standoffs is where the local standoffs are pressure sensitive resistors. Pressure sensitive resistors have a resistance which depends on applied pressure, and can therefore provide the dual functions of switch element and spacer in embodiments of the invention. For example, a post-shaped pressure-sensitive resistor can be in mechanical contact with both membrane and substrate in a pressure sensor element. When a fingerprint ridge makes contact with this sensor element, the resistor compresses and the resistance can drop below the detection threshold. When a fingerprint valley is aligned with this sensor element, the resistor is not deformed and its resistance is above the threshold.

FIGS. **8***a-b* show cutaway side and top views, respectively, of an embodiment of the invention including pressure sensitive resistors. More specifically, FIG. **8***a* shows a cutaway view along line **840** on FIG. **8***b*, and FIG. **8***b* shows a cutaway view along line **808** on FIG. **8***a*. This embodiment is similar to the embodiment of FIGS. **1***a-b*, except that pressure sensitive resistors (e.g., **820**, **822**, **824**, and **826**) extend from the substrate electrodes to the membrane electrodes. Here spacer **106** surrounding the pressure sensor elements is preferably present, although it can be omitted.

A global cavity spacer advantageously requires reduced lateral alignment precision of the spacer compared to a local cavity spacer. Reduced alignment precision requirements significantly reduce manufacturing cost. This reduced cost is the main reason a global cavity spacer arrangement is preferred. However, a global cavity spacer configuration places significant demands on the mechanical design of the sensor, since the membrane is only supported at its edges and the substrate is flexible. These mechanical design issues are accounted for in the preceding description.

FIG. **5** shows remotely located row and column addressing circuitry for use with the invention. A sensor **502** having an array of pressure sensor elements **550** is connected to column addressing circuitry **508** by column connections **504**. Sensor **502** is also connected to row addressing circuitry **510** by row connections **506**. In this exemplary embodiment, sensor **502** can have the configuration shown in FIGS. **1***a-b*. As indicated above, it is desirable for sensor **502** to be an entirely passive device (i.e., including no active electrical devices such as transistors), in order to reduce the cost of sensor **502**.

Row and column addressing circuitry can be connected to such a passive sensor in any convenient manner. For example, circuitry **508** and **510** can be implemented as application specific integrated circuits (ASICs), and the ASIC chips and sensor **502** can be disposed on a common substrate including connections **504** and **506**. Alternatively, the common substrate can be substrate **102** of sensor **502**, and can have connections **504** and **506** defined on it via some of the processing steps used to fabricate sensor **502**. Hybrid integration of ASIC chips with such a structure is straightforward. The overall cost of such hybrid integration approaches can be much lower than monolithic integration of the circuitry with sensor **502**.

FIGS. **6***a-c* show a preferred sequence of processing steps for fabricating part of an embodiment of the invention. More specifically, substrate features such as electrode **110**, resistors **120**, **122**, **124**, and **126**, and contact layers **130**, **132**, **134**, and **136** on FIG. **1***a* are preferably fabricated with a self-aligned process. The first step of this process is deposition of an electrode layer **604** on a substrate **602**, followed by deposition of a resistor layer **606** on electrode layer **604**, followed by deposition of a contact layer **608** on resistor layer **606**. FIG. **6***a* shows the result of this first step. In some cases, it is preferred to also deposit a barrier layer (not shown) after deposition of resistor layer **606** and before deposition of contact layer **608**. Such barrier layers are known in the art. For example, if the contact layer is gold, and the resistor is silicon, then a Ti-W barrier layer is suitable. A barrier layer may also (or alternatively) be disposed between the substrate electrode and the resistor. Additionally, it may be advantageous in some cases to deposit an adhesion layer to enhance the adhesion between the electrode and the substrate. For example, if the electrode is gold, and the substrate is polyimide, a thin chromium layer can be used to enhance adhesion.

The second step, shown on FIG. **6***b*, is coating and patterning of a mask layer **610** (e.g., a photoresist, electron beam resist, etc.). To obtain the configuration of FIG. **1***b*, the pattern of mask layer **610** is a series of parallel lines, shown in end view on FIG. **6***b*. The third step is etching away the unprotected parts of layers **608**, **606**, and **604**, to form lines in layers **608**, **606**, and **604**, followed by removal of mask layer **610**. As a result of this processing sequence, the resistor and contact layer lines are advantageously both aligned with the electrode lines. Further processing, which is also preferably self aligned with respect to contact layer **608** and resistor layer **606**, can be employed to define multiple discrete resistors (each having its top contact) on each substrate electrode, as shown on FIGS. **1***a-b*. Alternatively, with the appropriate resistivity for the resistor layer, and a thin enough resistor layer, the resistor layer can be left continuous, and discrete contacts alone can be defined at this step of the process.

FIGS. **7***a-b* show bonding methods suitable for fabricating some embodiments of the invention. A significant advantage of the invention is that it allows for the possibility of fabricating large numbers of pressure sensor arrays simultaneously. More specifically, the flexibility of the substrate and membrane allows for a "roll-to-roll" fabrication model, as opposed to the significantly more costly "wafer" model entailed by having a rigid substrate.

FIG. **7***a* schematically shows a first roll to roll fabrication process. A flexible substrate is processed (e.g., using processes described above) to form a substrate pattern. Similarly, a flexible membrane is processed to form a membrane pattern. The patterned substrate **708** and patterned membrane **706** are bonded by passing through rollers **702** and **704** to provide a bonded structure **720**. The membrane and substrate patterns combine to form pressure sensor elements in bonded structure **720** (e.g., as shown on FIGS. **1***a-b* and **2***a-b*). More specifically, a spacer (such as **106** on FIGS. **1***a-b*) is formed by the combination of substrate and membrane patterns. Since the substrate is flexible, the process inputs (i.e., **706** and **708**) can be provided from rolls of patterned material, and the process output **720** can be taken up on a roll of bonded sensors. Patterning of the membrane and substrate and incorporation of circuitry (e.g., as shown on FIG. **5**) can also be performed at the roll level. Cost is reduced by performing all processing at the roll level except for final division into discrete assembled sensors.

In a preferred embodiment, the process of FIG. **7***a* is used to fabricate a pressure sensor element array having a spacer which includes pressure sensitive resistors as local standoffs. More specifically, patterned substrate **708** (and/or patterned membrane **706**) include pattern features that form pressure sensitive resistors acting as the spacer after bonding substrate and membrane together.

FIG. **7***b* schematically shows a second roll to roll fabrication process. The process of FIG. **7***b* is similar to that of FIG. **7***a*, except that a patterned spacer **710** is included as a process input, and a bonded structure **730** is basically a three layer sandwich structure having substrate, spacer and membrane. Spacer **710** can be provided as a patterned film, or can be deposited in a patterned manner on the substrate and/or the membrane. The examples of FIGS. **7***a-b* are only two of many ways to fabricate embodiments of the invention.

The present invention is widely applicable. In broad terms, sensors such as those described above provide an output signal from one or more pressure sensor elements. This output signal can take various forms. The output signal can be an image of a textured surface (e.g., a fingerprint image), obtained by polling some or all of the sensor elements. The output signal can also be a binary touch signal, responsive to at least one of the pressure sensor elements.

A typical use for a binary touch signal is to "wake up" a device in standby mode in response to a touch from a user. Other applications of binary touch signals include power switch systems, menu selection systems, pointer activation systems, and standby/wakeup systems.

Applications of image signals where the textured surface is a fingerprint include identification systems, security systems, motion sensing systems, and cursor control systems. Motion sensing can be accomplished using image signals by comparing two images of the same fingerprint taken at different times. Comparison of the two images will provide information on how the finger has moved. In turn, this motion information can be used for various applications, such as cursor control for a computer input device. Such comparison of images is facilitated by selecting a subset of the image points to be compared, in order to reduce the required computation time.

Some aspects of the invention can be appreciated by consideration of the following illustrative example. This example is a fingerprint sensor having the configuration shown in FIGS. **1***a-b*. The sensor array has 256 rows and 256 columns. The membrane and substrate are made of PET, PEN or Kapton® (a polyimide), and the spacer is a pressure sensitive adhesive. The membrane thickness is 12.5 μm, the substrate thickness is 50 μm, and the spacer thickness is 20-50 μm. The row electrodes are 100 nm thick, 35 μm wide and have a center to center spacing (i.e., pitch) of 50 μm. The column electrodes are 100 nm thick, 15 μm wide and have a pitch of 50 μm. The row and column electrodes in this example differ in order to provide increased contact area and increased alignment tolerance simultaneously. The resistors are silicon resistors having a value of 1 MΩ. A 100 nm thick gold contact layer is on top of the resistors, and a Ti-W barrier layer is between the contact layer and the resistor layer for each resistor.

Further embodiments of the invention relate to access control systems including a fingerprint authentication subsystem, where the authentication subsystem includes a flexible sensor as described above. The authentication subsystem is preferably an integrated assembly including a pressure sensor according to the invention and electronic circuitry connected to the pressure sensor.

The authentication subsystem can provide various functions, such as fingerprint image capture, fingerprint image processing, fingerprint image storage, fingerprint matching, authentication, encryption, cursor control, on/off switching, access control, transaction authorization, wireless communication, and location determination. Such subsystem functions are useful in various kinds of access control systems, including but not limited to: smart cards, credit cards, identity cards, microprocessor cards, integrated circuit cards, embedded mobile electronics, embedded consumer electronics devices, computer peripheral devices, and physical installations having access control. The ability to provide fingerprint sensing and authentication for such diverse applications is a key advantage of the invention, since many of these applications have requirements which are incompatible with rigid fingerprint sensors.

FIGS. **9***a-b* show top and side views, respectively, of an integrated fingerprint authentication subsystem according to an embodiment of the invention. In the embodiment of FIGS. **9***a-b*, the pressure sensor elements of the pressure sensor are all included within a sensor array area **902**, and electronic circuitry is disposed on the flexible sensor substrate **102** at one or more locations outside the sensor array area. This embodiment can be regarded as monolithically integrated, since the flexible sensor substrate **102** also acts as the substrate for the additional electronics. In the example of FIGS. **9***a-b*, sensor control electronics **906** and **912**, a microprocessor **910**, input/output pins or pads **908**, and a flexible thin film battery **914** are shown. Battery **914** can provide electrical power to the sensor and/or to the other integrated electronics. These components can be electrically connected to each other and/or to the pressure sensor elements within array area **902** using known approaches (e.g., formation of suitable conductive traces on substrate **102**).

FIG. **9***b* shows a side view along line **904** of FIG. **9***a*. Electronic circuits can be disposed on the top and/or bottom surfaces of sensor substrate **102**. Some possible positions (e.g., position **930**) for circuitry are shown with dotted lines on FIG. **9***b*. The arrangement of FIGS. **9***a-b* can be made compact. For example, a package outline **920** surrounding this integrated subsystem is shown on FIG. **9***b*. Typical outer dimensions for such a package are less than about 25.4 mm by 25.4 mm lateral dimensions and less than about 0.5 mm thickness.

To facilitate compact integration, circuitry (e.g., **906**, **910**, and **912** on FIG. **9***a*) is preferably disposed on sensor substrate **102** as one or more unpackaged integrated circuit chips. Wire bonding and flip chip bonding are two suitable techniques for making electrical contact between such a chip and other electrical components (e.g., traces on substrate **102** and/or other integrated circuits). Preferably, such chips are thinned to a thickness of less than about 200 μm, and more preferably to about 120 μm thickness, to reduce size.

Such circuitry is preferably provided as one or more application-specific integrated circuits (ASICs) having lateral dimensions less than about 5 mm by 5 mm. Such relatively small ASIC chips are more suitable for integration into flexible structures than larger ASIC chips, since ASIC chips are rigid. Readily available ASIC circuitry can significantly enhance the functionality of a pressure sensor. For example, such circuitry can include microprocessors, pressure sensor drive and sense electronics, and encryption circuitry. Such circuitry can also provide input/output functionality, such as support for serial interfaces such as GPIO, SPI, I^2C, ISO 7816, ISO 7810, and USB.

FIGS. **10***a-c* show several views of an integrated fingerprint authentication subsystem according to an alternate embodiment of the invention. FIG. **10***a* shows a pressure sensor **1002** having a flexible top membrane **104** which is connected to electronics on a separate electronics substrate **1006** by electrical connections **1004**. Pressure sensor **1002** can be any pressure sensor according to the present invention. A package outline **1008** is also shown. FIG. **10***b* shows a top view of a packaged version of this embodiment, where package **1010** surrounds the electronics on electronics substrate **1006** and surrounds all of pressure sensor **1002** except for flexible membrane **104** which is left exposed to a user's touch. FIG. **10***c* shows a side view of the packaged embodiment of FIG. **10***b* along line **1020**. This approach can be regarded as a hybrid integration approach, since electronics substrate **1006** is separate from sensor **1002**. The description of circuitry relating to the embodiment of FIGS. **9***a-b* also relates to this embodiment.

Electronics substrate **1006** is preferably made from a flexible material. Materials identified above as suitable for sensor substrate **102** are also suitable for electronics substrate **1006** (e.g., polyimides). Electronics substrate **1006** is preferably mechanically attached to sensor **1002** and electrically connected to sensor **1002**. Such mechanical attachment can be lateral (as shown on FIGS. **10***a-c*) or vertical. An example of vertical mechanical attachment is a configuration where electronics substrate **1006** is attached to the back side of sensor **1002** (i.e., the surface facing away from flexible membrane **104**).

Package **1010** is preferably made of a flexible material, and an outer surface of package **1010** is also preferably electrically conductive in order to provide protection of encapsulated circuitry from electrostatic damage (e.g., from electrostatic discharge). Injection molding and lamination are exemplary techniques for fabricating package **1010** surrounding the sensor and electronic circuitry. Other packaging techniques are also applicable to the present invention. In some preferred embodiments, tamper-detection components are included in package **1010**. For example, a photodiode inside an opaque package coupled to a one-time detection circuit can permanently trip the detection circuit if the package is opened to provide evidence of tampering. Any other package tampering detection methods can also be used in connection with the invention.

The embodiments of FIGS. **9***a-b* and **10***a-c* both preferably include unpackaged ASIC chips disposed on a flexible substrate. Since unpackaged ASIC chips tend to be rigid and mechanically fragile, it is preferred to provide stress relief for the ASIC chips. FIGS. **11***a-c* show various stress relief approaches suitable for use in integrated fingerprint authentication subsystems according to the invention. FIG. **11***a* shows a stress relief structure **1102** surrounding a chip **1104** disposed on a flexible substrate **1106**. This approach can be referred to as glob-top encapsulation, and curable epoxies are examples of suitable materials for stress relief structure **1102**. Here substrate **1106** can be either flexible sensor substrate **102** or electronics substrate **1006**. FIG. **11***b* shows chip **1104** disposed in a hollowed-out portion of substrate **1106** which acts as a stress relief feature. Hollowing and glob-top encapsulation can be combined, as shown on FIG. **11***c*.

The preceding description has been by way of example as opposed to limitation. Many modifications of the above examples are also included in the present invention. For example, the preceding description relates mainly to fingerprint sensing, but the invention is also applicable to sensing of any other textured surface.

The invention claimed is:

1. An access control system including a fingerprint authentication subsystem comprising:

a) an imaging pressure sensor for providing an image of a textured surface, the sensor comprising:

i) a flexible membrane conformable to the textured surface;

ii) a flexible sensor substrate, wherein said sensor substrate has a flexural rigidity D_S and said membrane has a flexural rigidity D_M, and wherein $D_M < D_S < 10^6 D_M$;

iii) at least two pressure sensor elements, wherein each pressure sensor element is responsive to a separation between a part of the membrane and a corresponding part of the sensor substrate; and

iv) a spacer disposed between and connected to the membrane and the sensor substrate;

wherein each of the separations has a corresponding non-zero nominal value determined in part by the spacer; and

b) electronic circuitry connected to the pressure sensor.

2. The system of claim **1**, wherein said electronic circuitry and said pressure sensor are encapsulated within a polymer package such that said flexible membrane is exposed.

3. The system of claim **2**, wherein an outer surface of said polymer package is electrically conductive, whereby protection against electrostatic damage is provided.

4. The system of claim **1**, wherein said electronic circuitry is disposed on an electronics substrate separate from said sensor substrate.

5. The system of claim **4**, wherein said electronics substrate comprises a flexible material.

6. The system of claim **4**, wherein said electronics substrate is mechanically attached to said pressure sensor and is electrically connected to said pressure sensor.

7. The system of claim **4**, wherein said electronic circuitry is wire bonded or flip chip bonded to said electronics substrate.

8. The system of claim **4**, wherein said electronics substrate includes stress relief features in proximity to said electronic circuitry.

9. The system of claim **4**, further comprising a stress relief structure in contact with said electronic circuitry and with said electronics substrate.

10. The system of claim **1**, wherein said pressure sensor elements are all included within a sensor array area; and wherein said electronic circuitry is disposed on said flexible sensor substrate at one or more locations outside the sensor array area.

11. The system of claim **10**, wherein said electronic circuitry is disposed on a top surface of said flexible sensor substrate or on a bottom surface of said flexible sensor substrate.

12. The system of claim **10**, wherein said electronic circuitry comprises an unpackaged integrated circuit chip.

13. The system of claim **10**, wherein said electronic circuitry is wire bonded or flip chip bonded to said flexible sensor substrate.

14. The system of claim **10**, wherein said flexible sensor substrate includes stress relief features in proximity to said electronic circuitry.

15. The system of claim **10**, further comprising a stress relief structure in contact with said electronic circuitry and with said flexible sensor substrate.

16. The system of claim **15**, wherein said integrated circuits have lateral dimensions less than about 5 mm by 5 mm.

17. The system of claim **15**, wherein said integrated circuits include a circuit selected from the group consisting of: microprocessors, pressure sensor drive and sense electronics, location determination circuitry, wireless communication circuitry, and encryption circuitry.

18. The system of claim **15**, wherein said integrated circuits have a thickness less than about 200 μm.

19. The system of claim **1**, wherein said electronic circuitry comprises interface circuitry for a serial standard selected from the group consisting of: GPIO, SPI, I^2C, ISO 7816, ISO 7810 and USB.

20. The system of claim **1**, wherein said electronic circuitry comprises one or more integrated circuits.

21. The system of claim **1**, wherein said subsystem provides one or more functions selected from the group consisting of: fingerprint image capture, fingerprint image processing, fingerprint image storage, fingerprint matching, authentication, encryption, cursor control, on/off switching, access control, transaction authorization, wireless communication, and location determination.

22. The system of claim **21**, wherein said package has lateral dimensions less than about 25.4 mm by 25.4 mm and has a thickness less than about 0.5 mm.

23. The system of claim **1**, wherein said access control system is selected from the group consisting of: smart cards, credit cards, identity cards, microprocessor cards, integrated circuit cards, embedded mobile electronics, embedded consumer electronics devices, computer peripheral devices, and physical installations having access control.

24. The system of claim **1**, further comprising a protective package surrounding said electronic circuitry and surrounding all of said sensor except said flexible membrane.

25. The system of claim **1**, further comprising a flexible thin film battery providing electrical power to said sensor and to said electronic circuitry.

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